

Development of a Heterogeneous sUAS High-Accuracy Positional Flight Data Acquisition System

*Robert G. McSwain
Langley Research Center, Hampton, Virginia*

*Ferdinand W. Grosveld
Northrop Grumman, Hampton, Virginia*

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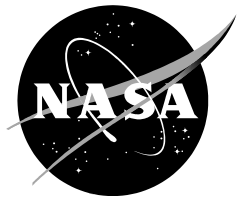
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*Robert G. McSwain
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National Aeronautics and
Space Administration

*Langley Research Center
Hampton, VA 23681*

August 2016

Acknowledgments

The authors gratefully acknowledge the Aeronautics Research Mission Directorate Convergent Aeronautics Solutions Design Environment for Novel Vertical Lift Vehicles project which supported this work through NASA Langley Research Center. Special appreciation goes to Collin Baker (NASA Intern) for writing a custom program to parse satellite RINEX file data. Charles Howell (Langley Research Services Directorate) also provided key contributions with GPS survey knowledge and equipment.

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Acronyms

ASRB – Airworthiness & Safety Review Board
CAS – Convergent Aeronautics Solutions
CONOPS – Concept of Operations
COTS – Commercial Off-The-Shelf
DELIVER – Design Environment for Novel Vertical Lift Vehicles
DGPS – Differential Global Positioning System
EMI – Electromagnetic Interference
ERA – Environmentally Responsible Aviation
FDAS – Flight Data Acquisition System
FTOSR – Flight Testing Operational Safety Report
GBP – GPS Benchmark Point
GPS – Global Positioning System
ICD – Interface Control Document
ITD – Integrated Technology Demonstration
LiPo – Lithium Polymer
PIC – Pilot in Command
RINEX - Receiver Independent Exchange Format
RTK- Real Time Kinematic
sUAS – small Unmanned Aerial System
UTC – Coordinated Universal Time

1. Introduction

Recently, a heterogeneous FDAS, consisting of a diverse range of instruments was developed to support acoustic flight research programs at NASA Langley Research Center. In addition to a conventional GPS to measure latitude, longitude and altitude, the FDAS also utilizes a small, light-weight, low-cost DGPS system to obtain centimeter accuracy to measure the distance traveled by sound from a sUAS vehicle to a microphone on the ground. Acoustic flight testing using the FDAS installed on several different sUAS platforms has been conducted in support of the NASA CAS DELIVER and ERA ITD projects (Reference 1).

The first FDAS prototype was assembled and implemented in the acoustic/flight measurement system in December 2014 to support DELIVER acoustic flight tests. Evaluation of the system performance and results from the data analyses were used to further test, develop and enhance the FDAS over a six-month period to support acoustic flight research for the ERA ITD and DELIVER programs at Fort A.P. Hill Army Base in September 2015. The goal of this technical memorandum is to discuss the FDAS conceptual design, its development, operation, testing and resulting data during flight research conducted using the system between December 2014 and September 2015.

2. Conceptual Design

The FDAS was designed utilizing available low-cost COTS components to include a 3DR Pixhawk Auto-Pilot and a Swift Navigation Piksi DGPS module. The initial DELIVER sUAS FDAS platform was designed for a DJI Phantom 2. Position data with UTC timestamps were required [Table 1] for use in conjunction with acoustic data for post flight analysis/research. In addition, data was acquired for aircraft attitude, aircraft velocity, atmospheric temperature and atmospheric pressure as tabulated in Table 1.

Table 1: Acoustic Testing Flight Data

Aircraft Position (Required)	Altitude
	Latitude
	Longitude
Aircraft Attitude (Desired)	Pitch
	Roll
	Yaw
Aircraft Velocity (Desired)	Ground Speed
	Airspeed
Atmospheric Parameters (Desired)	Temperature
	Pressure
Timestamp (Required)	UTC Time

The primary considerations for the FDAS design included developing a reliable positioning system producing highly accurate results, functioning independently from the primary flight avionics, and being interchangeable on multiple aircraft. The FDAS system is composed of a rover and base station [Figure 1]. The rover unit consists of commercially available Pixhawk (3DR Robotics) and Piksi (Swift Navigation) modules. The Pixhawk is an open source auto-pilot system which provides attitude, GPS and pressure data with corresponding UTC timestamps. The Piksi is an open source RTK GPS positioning system which was used to provide DGPS data with the corresponding UTC timestamps. Using readily available low-cost COTS

components enabled rapid development, testing and integration to be completed in less than two months, prior to the proposed flight research in December 2014. Swift Navigation developers were actively working on integrating the Piksi DGPS into the Pixhawk at that time but the documentation and firmware needed had not yet been released. Therefore only power was supplied to the Piksi, using a serial port on the Pixhawk. Important to note though is that as of June 2015 the Piksi/Pixhawk integration is supported and released by Swift Navigation and 3DR developers.

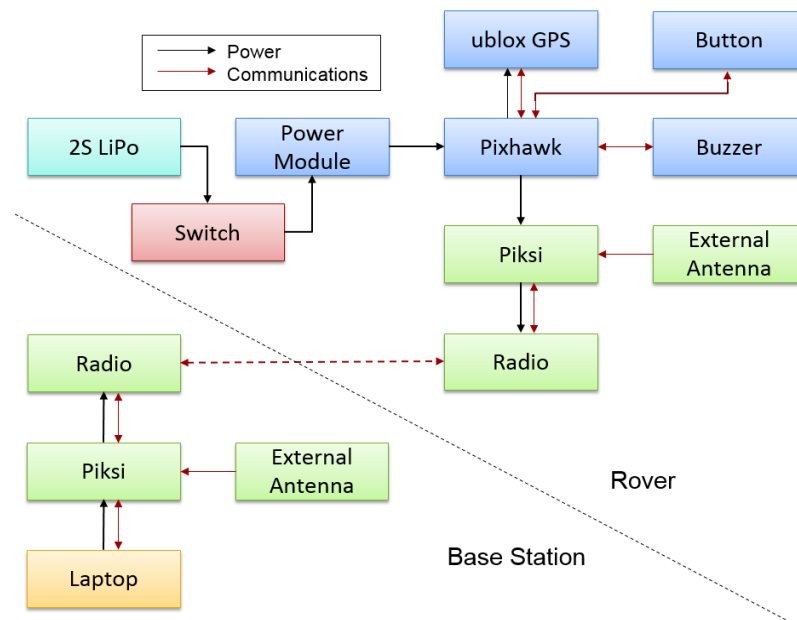


Figure 1: FDAS System Diagram

Several additional sUAS were available for flight testing at NASA Langley Research Center [Figure 2]: Y6 (3DR Y6), Edge 540 (Hangar 9 33% Scale Edge 540), and MigLH (FQM-117B). These aircraft have a wide range of performance specifications to include airspeed, payload and maneuverability. The primary reason for these vehicles being selected was availability. All the vehicles minus the Phantom 2 were flight ready and available on center for use in this research effort.



DJI Phantom 2 (13.8 in. Diagonal Length)



3DR Y6 (20 in. Diagonal Length)



Hangar 9 Edge 540 (68 in. Wingspan)



FQM-117B (68 in. Wingspan)

Figure 2: Proposed sUAS for flight testing

Referencing NASA Langley's ASRB FTOSR, a flight testing CONOPS [Figure 3] was created to develop the processes and procedures needed to conduct flight testing using the FDAS. Major considerations for the CONOPS included safety, reliability and available test site limitations/considerations.

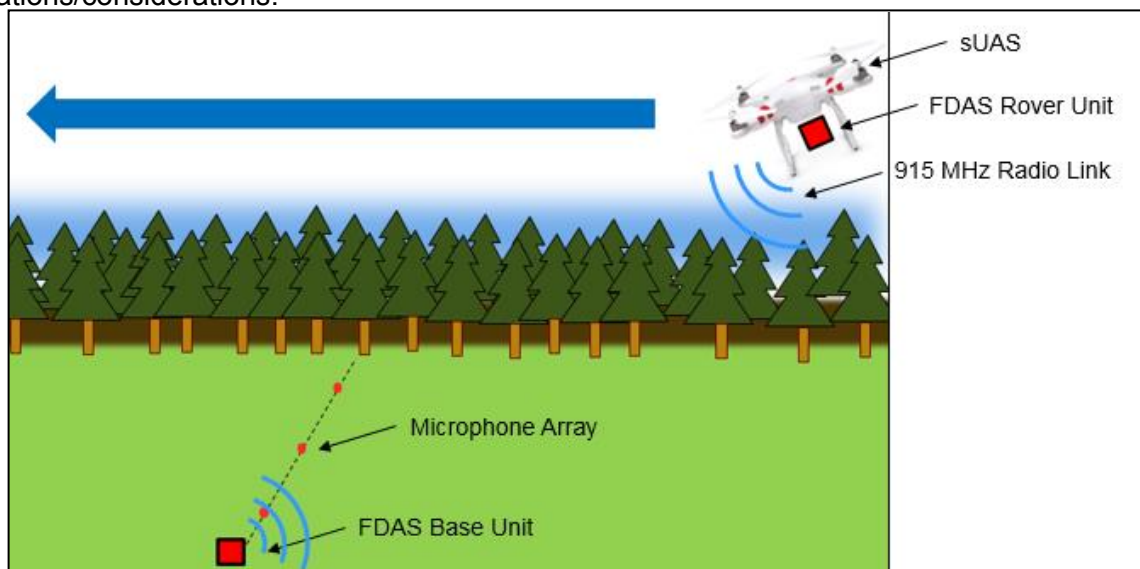


Figure 3: Acoustic Flight Test CONOPS

3. Development

The FDAS was developed through a rapid iterative process. Although several configuration changes occurred over the development process, only configurations used during flight research are considered prototypes in this document. The first prototype [Figure 4] which weighed 590 g (1.3 lbs.) and operated using 350 mA consisted entirely of COTS hardware and software:

- 3DR Pixhawk Auto-Pilot, ArduPlane v3.2.0
- 3DR Pixhawk Buzzer
- 3DR Pixhawk 2-position Button
- 3DR Pixhawk Power Module
- 3DR Pixhawk uBlox GPS/Compass Module
- Thundercat 3S 2000mAh LiPo Battery
- Swift Navigation Piksi OEM Module (x2), Piksi STM v.13/Piksi NAP V.10
- Linx ANT-GPS-SH-SMA External Antenna (x2)
- 3DR 915MHz Telemetry Radio (x2)

- LDM Industries Inc. Plastic Enclosure
- Aluminum Rectangular Ground Plane
- 25 ft. USB Extension Cable
- Windows Operating System Laptop, Pixi Console v.12

The unit was attached to the aircraft using high-strength 3M fasteners. This prototype was used on 17 December 2014 during CAS DELIVER acoustic flight research conducted at Virginia Beach Airport (42VA). After the December flight tests a 3D printed enclosure was designed to reduce weight, decrease volume and decrease drag for future testing. Another benefit of using a 3D printed enclosure was to provide a fast customized attachment point for any future proposed sUAS aircraft.



Figure 4: FDAS Prototype 1

The second prototype [Figure 5], which weighed 410 g (0.9 lbs.) and operated with 400 mA, added a 900 MHz radio to provide real-time GPS information through Mission Planner. This feature was needed to get an indication how close the aircraft passed over the center of the microphone array. The components of the second prototype included:

- 3DR Pixhawk Auto-Pilot, ArduPlane v3.2.0
- 3DR Pitot Tube Module (Optional)
- 3DR Pixhawk 2-position Button
- 3DR Pixhawk Power Module
- 3DR Pixhawk uBlox GPS/Compass Module
- 1S 1200 mAH LiPo Battery (x2)
- Swift Navigation Pixi OEM Module (x2), Pixi STM v.18/Pixi NAP v.14
- Linx ANT-GPS-SH-SMA External Antenna (x2)
- 3DR 915 MHz Telemetry Radio (x4)
- Nylon Material 3D Printed Plastic Enclosure (x2)
- Aluminum Circular Ground Plane (x2)

- 25 ft. USB Extension Cable
- Windows Operating System Laptop, Pixi Console v.23/Mission Planner v1.3.30
- Sunpak 200IUT Tripod

A power switch was added to allow the batteries to be placed inside the enclosure. The rover unit was attached to the aircraft through a 3D printed attachment mounted on the aircraft using high-strength 3M fastener tape. The mounting location on each vehicle could be adjusted with the fastener attachment method to ensure all aircraft were balanced according to the vehicle flight requirements. The attachment used a rail mechanism to allow the enclosure to slide and lock into position versus having to use tools to take off the cover. The rover unit was locked into position using a wire tie. This prototype was used on 27 August 2015 during ERA ITD and DELIVER acoustic flight testing at Fort A.P. Hill.

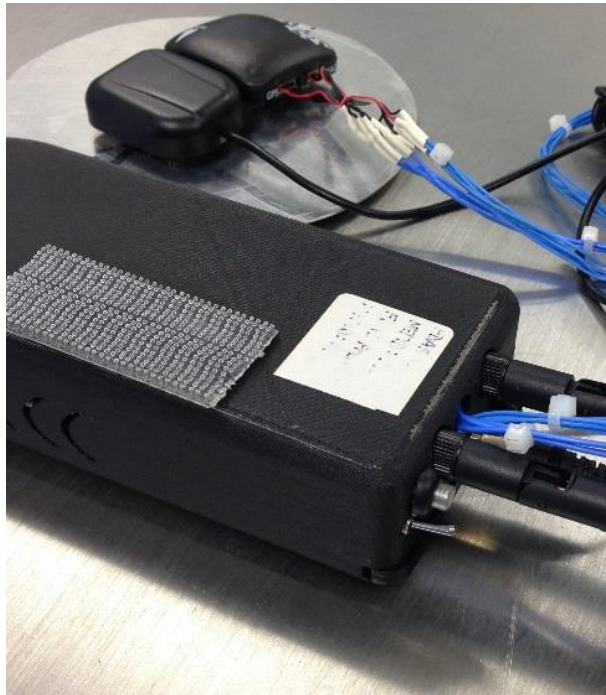


Figure 5: FDAS Prototype 2

4. Field Operation

The FDAS CONOPS includes two phases. The first phase establishes an aircraft starting position so that an RTK relative position vector between the base and rover can be recorded. The second phase displays real-time relative and absolute aircraft position for the FDAS operator and logs the data. The following steps were used in operating the FDAS during flight research experiments on 27 August 2015:

- Survey the base antenna location prior to conducting the flight test.
- Deploy base station at surveyed location, to include setting up the tripod and laptop workstation.
- Energize the base station by connecting the Pixi and laptop using a Micro USB to USB cable.
- Run the Pixi Console application on the laptop, select the appropriate COM port.
- Connect the Pixhawk 3DR Radio to the laptop using a Micro USB to USB cable.

- Run the Mission Planner application on the laptop, select the appropriate COM port.
- Insert and connect charged batteries on the rover unit.
- Attach the rover unit to the aircraft as per the ICD generated by the flight crew.
- Energize the rover unit by toggling the power switch to on.
- Through Mission Planner connect the application to the Pixhawk.
- Place the aircraft in a take-off position and allow the Pixi to establish a Fixed-RTK solution so that the base and rover external antenna relative distance is measured and recorded with the Pixi.
- For future flights the baseline recorded measurement was input into the “Settings” tab and the base station was initialized using “Initiate with known baseline” on the “Baseline” tab in the Pixi Console application.
- Verify the base station is in a Fixed-RTK mode of operation.
- On the “Observations” tab, select “Save” for the rover and base observations to begin generating RINEX observations files for the flight.
- Inform the sUAS PIC the system is ready and he could begin take-off.
- Monitor the system and provide information as requested from ground personnel or flight crew (Altitude, Slant Range, etc.).
- After the aircraft lands stop the RINEX file recording and de-energize the rover unit.
- Record the time the rover unit was de-energized.

After flight operations, there are several data files generated for post-flight analysis. The Pixi Console application generates Baseline, Velocity, and Position “.CSV” files on the laptop. The Pixhawk generates a flight log “.BIN” file onboard. Mission Planner generates a telemetry log “.TLOG” on the laptop. Both the Pixhawk and Mission Planner data files can be viewed and converted to other file formats using Mission Planner.

5. Testing and Results

Prior to using the FDAS in the acoustic flight research several ground tests were conducted to measure the system performance. The Pixhawk GPS solutions were expected to provide reliable/robust 3 m (9.84 ft.) latitude/longitude data and 10 m (32.8 ft.) altitude data. The Pixi DGPS was expected to provide a high-accuracy (centimeter) relative position data between the base and rover external antennas. The Pixi was in development during that time and therefore the reliability and robustness of the DGPS position data were unknown. The focus of the FDAS performance was on the DGPS position data and how it compared to the GPS position data.

The first “ground” test was conducted on the roof of a building at NASA Langley [Figure 6] on 1 December 2014 to validate the DGPS centimeter relative altitude accuracy. The rover and base external antennas were placed adjacent to one another to initialize the “Fixed RTK” mode of operation. Once the system had a “Fixed RTK” solution the external antennas were separated. A measuring tape was used to measure the reference distances.

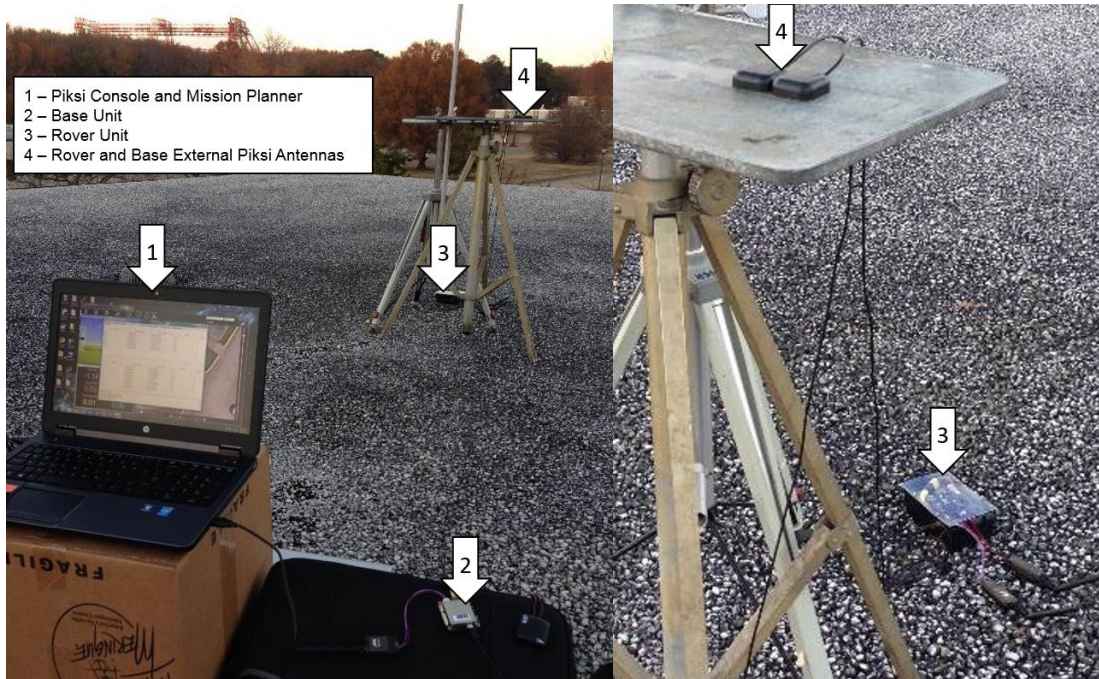


Figure 6: Ground Test Setup

Three separate data sets were collected to evaluate the DGPS position data. The first data set tested the relative altitude accuracy. In the data plots [Figure 7] color was used to represent time. This helped correlate relative altitude changes and relative lateral changes. The entire data set was divided into five sections, each assigned a color. As seen in the Figure 7, the beginning of the data is red and the end of the data is black. The elevation over time plot shows the RTK position data during the 1 m (3.28 ft.) vertical displacement. The highest recorded error was approximately 5 cm. This was determined by looking at the data between $T=200$ and $T=1100$ and recording the highest offset from the approximate measured value of $\sim 1\text{m}$ (3.28 ft.) using measuring tape.

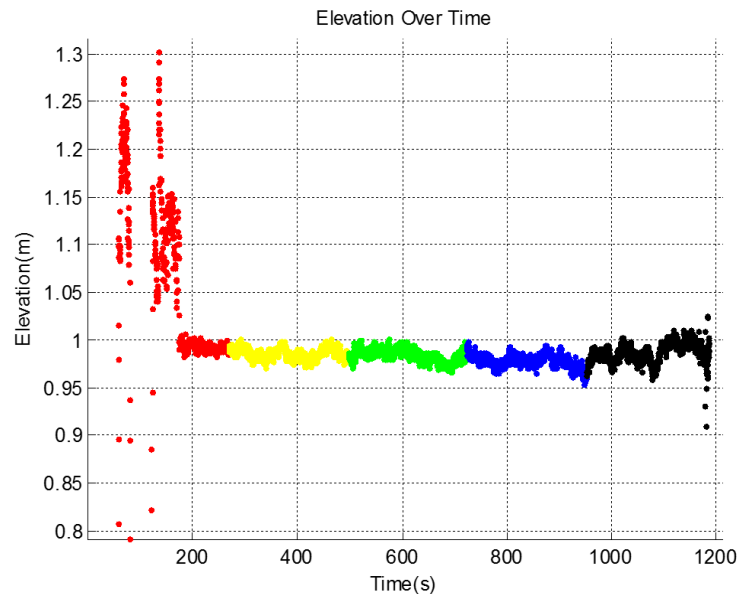


Figure 7: DGPS Relative Altitude Data

The second data set measured the relative north and relative east position data. The rover unit was placed 10 m (32.8 ft.) from the base unit. An approximate distance was determined by placing a tape measure on the ground surface and holding the rover unit DGPS external antenna over the 10 m (32.8 ft.) marking. The relative north and east position data [Figure 8] show the lateral displacement to be approximately 9.7 m (31.8 ft.). The highest recorded error was about 0.3 m (12 in.). This was determined by looking at the data starting from T=470 and T=520 and recording the highest offset from the approximate measured value of 10m (32.8 ft.) using measuring tape.

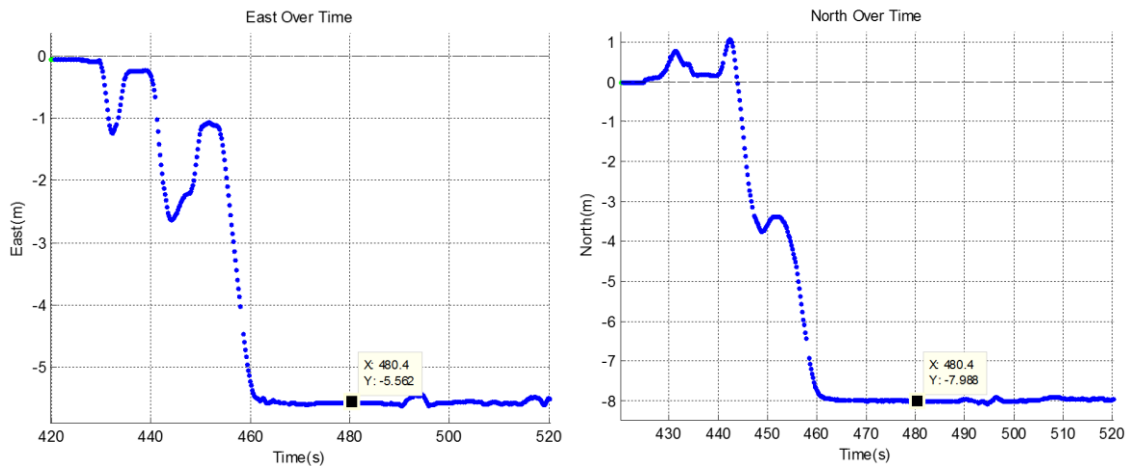


Figure 8: DGPS Relative East and North Data

The third data set collected [Figure 9] measured the dynamic performance by walking the rover unit tracing the perimeter of the rooftop. The Piksi Console application provides a real-time north/east relative position plot; therefore observations of the DGPS data were viewed.

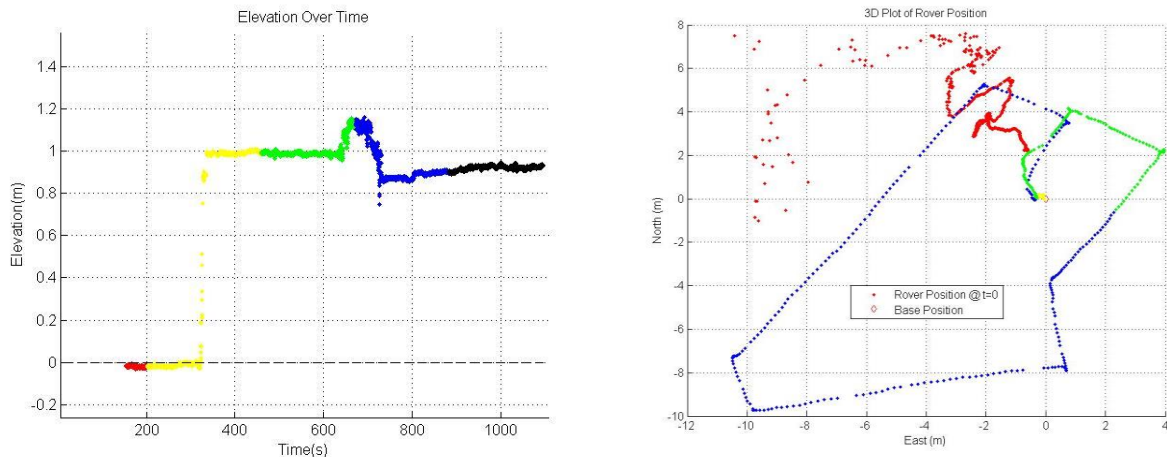


Figure 9: DGPS Dynamic Data

Afterwards the data were compared to an aerial image of the test location [Figure 10].



Figure 10: Aerial Image of Ground Test Location

The first acoustic flight test was conducted at Virginia Beach Airport on 17 December 2014 using the first prototype FDAS [Figure 11] for aircraft position and attitude data. Flight research was conducted using a single FDAS for four different research aircraft (MigLH, Edge 540, Phantom 2, Y6). Over two days twelve research flights were completed.



Figure 11: Acoustic Flight Research Conducted At Virginia Beach Airport

A DGPS performance difference was observed between fixed-wing and multi-rotor flights. For fixed-wing flights the majority of DGPS data were designated “Float,” which indicates nominal GPS accuracy. This loss of a “Fixed-RTK” solution [Figure 12] occurred shortly after

take-off on all fixed-wing flights. DGPS data in Figure 12 show that after the loss of RTK solutions, the float position error slowly moves outside of even nominal GPS accuracy. Therefore, any DGPS data after a loss of RTK were associated with an unknown error. For multi-rotor flights the majority of DGPS data were “Fixed-RTK” having centimeter accuracy [Figure 13]. During RTK mode the distance between the DGPS and GPS solutions represents an approximate GPS error.

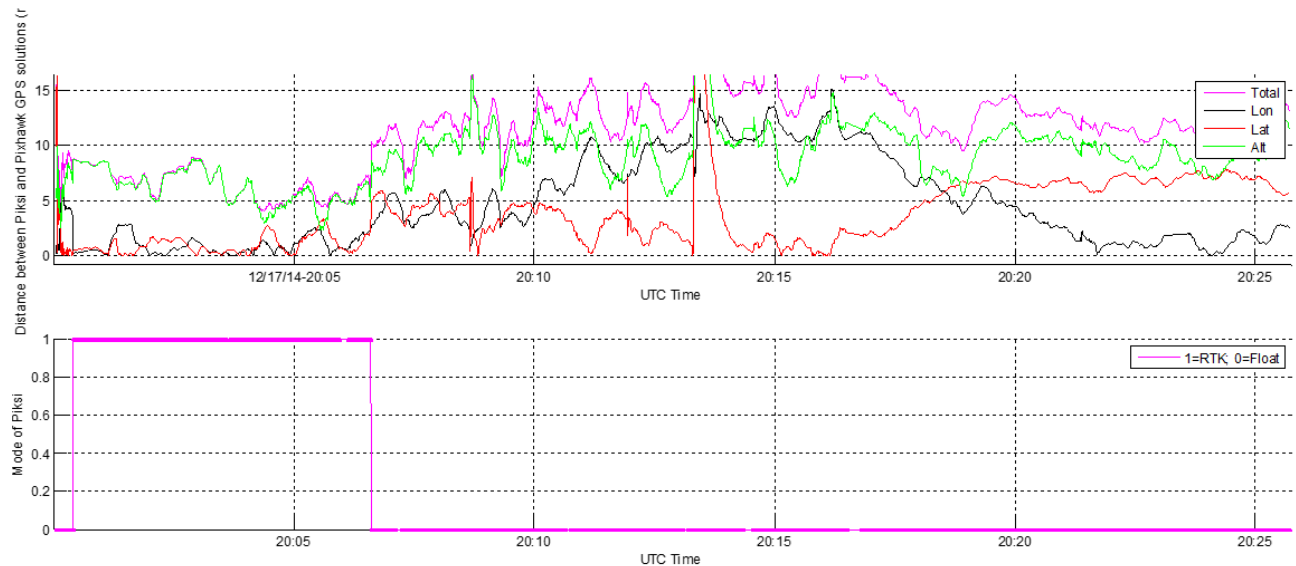


Figure 12: Distance between GPS and DGPS Position During MigLH Flight

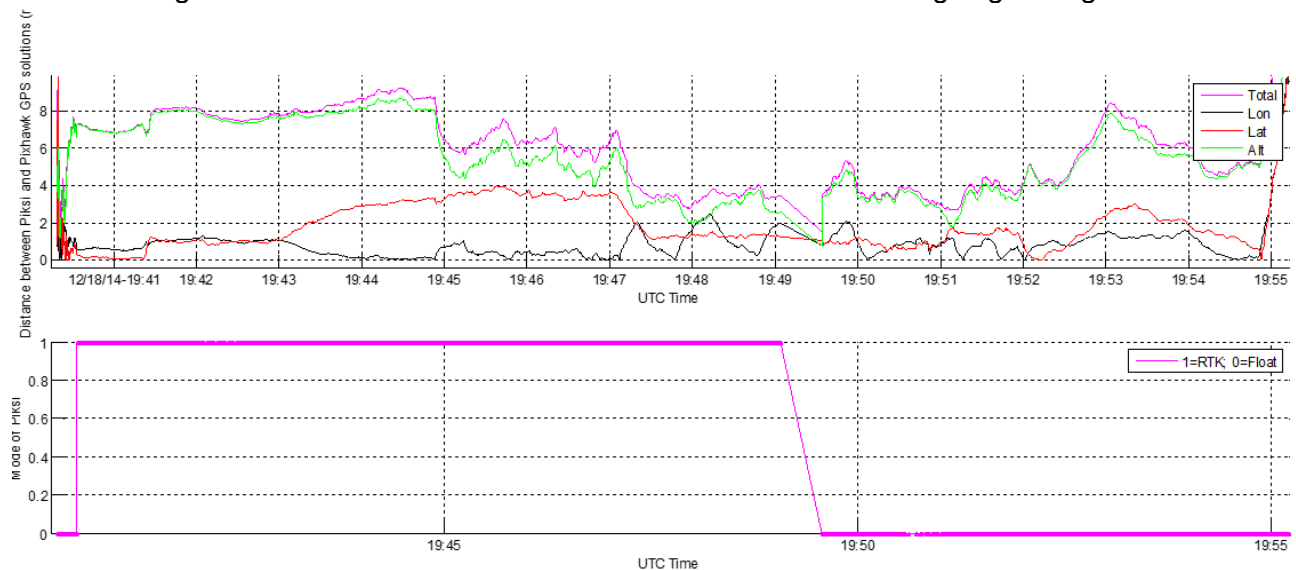


Figure 13: Distance between GPS and DGPS Position During Phantom 2 Flight

After analyzing the DGPS data from Virginia Beach Airport additional ground testing was conducted [Figure 14] at NASA Langley to validate the RTK position data at an increased range. During the test, the base unit was positioned over a surveyed monument (NASA25). The ground was marked with a 30 m (105 ft.) measuring tape. The rover unit was mounted to a telescopic stand. A bubble level indicator was used to keep the stand vertical. The telescopic stand was placed at 30.5m (100 ft.) [Figure 15], 27.4m (90 ft.), 21.3m (70 ft.), and 12.2m (40 ft.) during the ground tests.



Figure 14: Ground Testing Setup

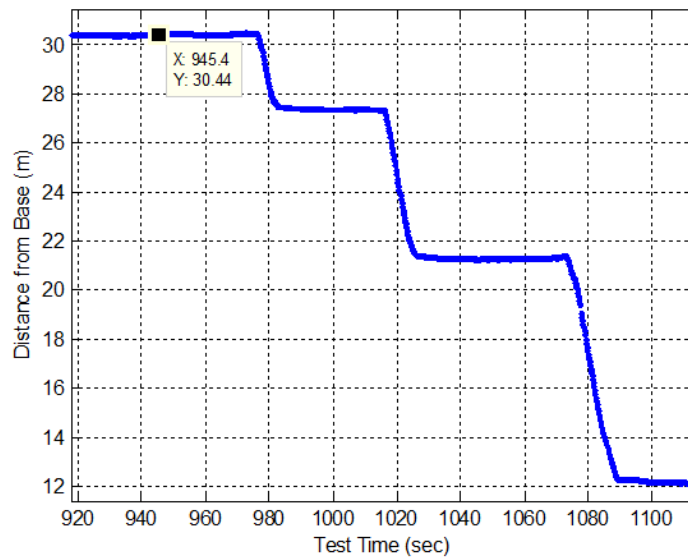


Figure 15: DGPS Relative Distance Data

In order to benchmark both the DGPS and GPS data, four survey markers [Figure 16] were placed near the NASA 25 monument. These markers were surveyed with centimeter accuracy using an Ashtech Z-Xtreme GPS Receiver. The Piksi firmware was also updated at that time to the following versions: Piksi Console V.23, Piksi STM V.18, and Piksi NAP V.14.



Figure 16: GPS Benchmark Points Surveyed At NASA Langley

A benchmark test was conducted at NASA Langley to compare the FDAS GPS and DGPS performance. A static test was conducted by placing the base unit on the NASA 25 monument and placing the rover unit on GBP2. GPS and DGPS data were collected for 5 minutes and the results showed the lateral DGPS solution to be accurate within 10 cm (3.9 in.) [Figure 17], compared to the lateral GPS solution accuracy of approximately 1.5m (4.92 ft.).

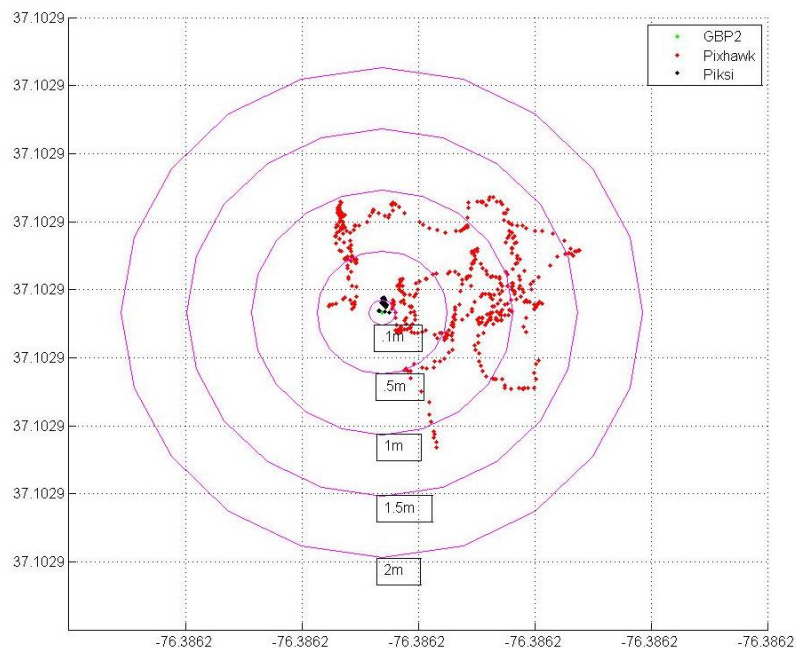


Figure 17: Static Benchmark Results

The dynamic test comprised of using a sUAS multi-rotor simulated flight path [Figure 18]. The rover unit was taken to GBP2 after it was initialized and then was used to trace the perimeter of the roadway. After the roadway was traced several circular flight paths were simulated while slowly increasing the bank angle. The data indicated that on average the DGPS solutions were reliable up to ~45° bank maneuvers. A minimum of five shared rover/base

satellite signals are required to achieve the “Fixed-RTK” solution. The second RTK loss during this test [Figure 19] provides a great example satellite signal being lost as the bank slowly increased until approximately 60° when only four satellite signals are detected on the rover and the DGPS solution is lost.

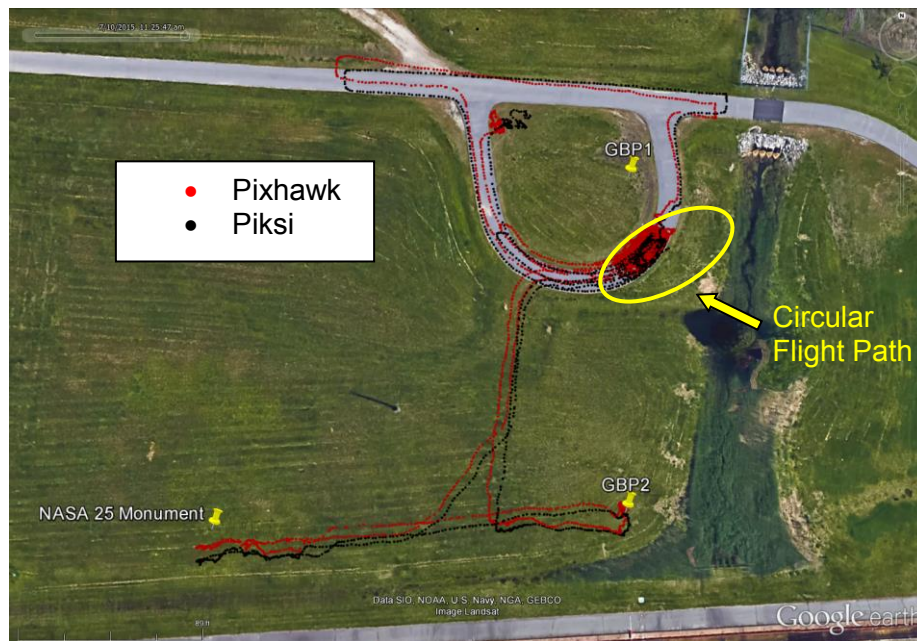


Figure 18: Simulated sUAS Flight Path

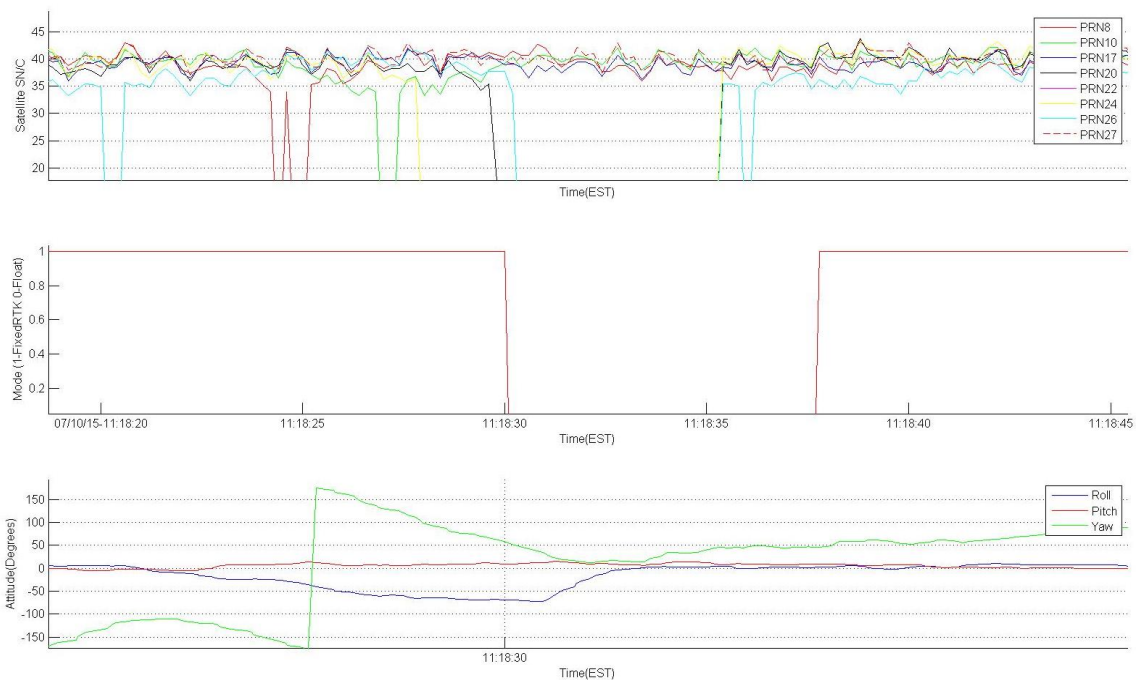


Figure 19: Circular Flight Path Fixed-RTK Loss

The second prototype FDAS was mounted and flown on three different sUAS [Figure 20] on 27 August 2015 in support of ERA ITD and DELIVER acoustic flight research. Over seven days twenty seven research flights were completed.



Carbon Cub



Hex Flyer



GL-10

Figure 20: Acoustic Flight Research Aircraft

Flight data from Fort A.P. Hill demonstrated an improvement in fixed-wing DGPS performance. The Carbon Cub flight data [Figure 21] show almost half of the flight having Fixed-RTK positional data. This can be observed on the plots by a magenta colored line where zero means float and a positive value means Fixed-RTK. The aircraft was performing at the limit of the system with roll and pitch angles greater than 45 degrees [Figure 22]. The DGPS rover satellite signals can be seen slowly fading in and out over the entire flight correlating with the attitude changes [Figure 23]. The distance between solutions over the entire flight can be seen in Figure 24. The GPS/DGPS plot is difficult to see because the DGPS solution was not providing a stable tracking solution.

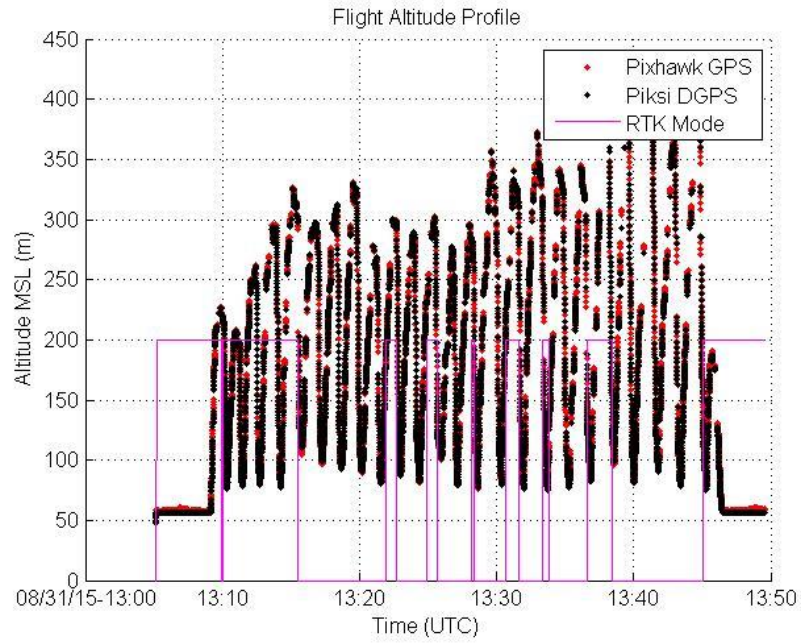


Figure 21: Carbon Cub Altitude

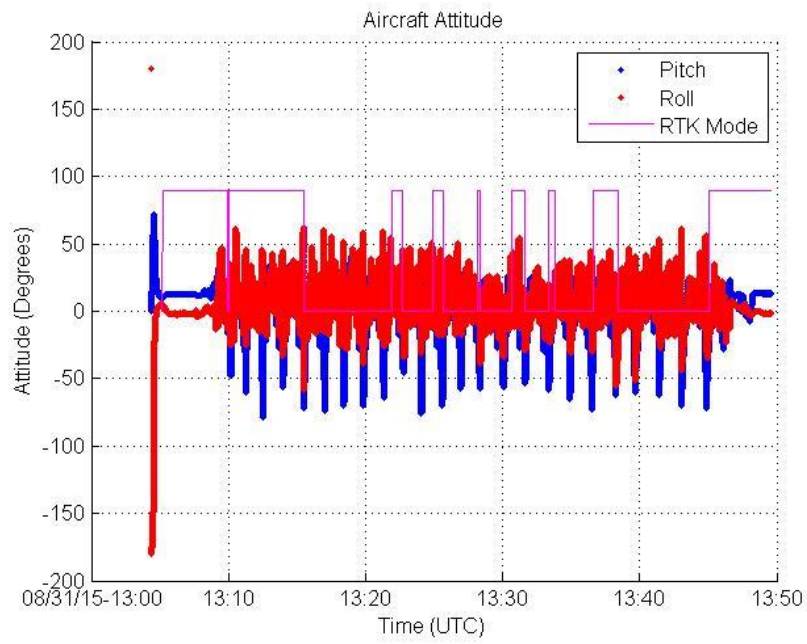


Figure 22: Carbon Cub Attitude

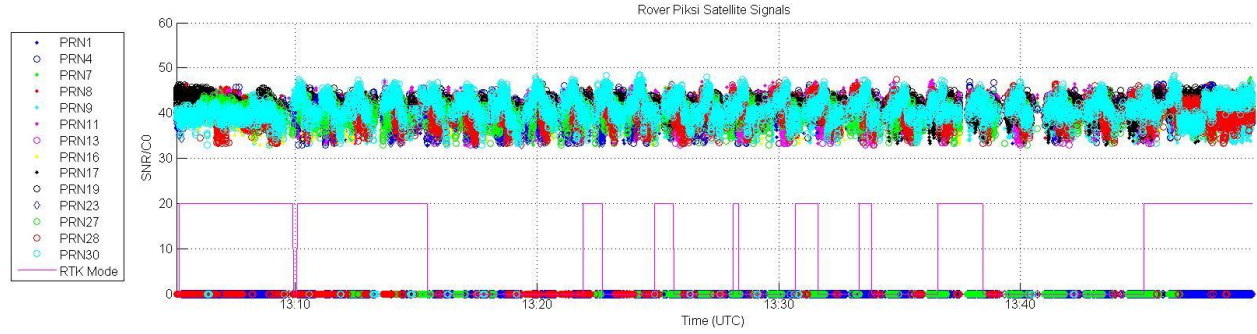


Figure 23: Carbon Cub DGPS Rover Satellite Signals

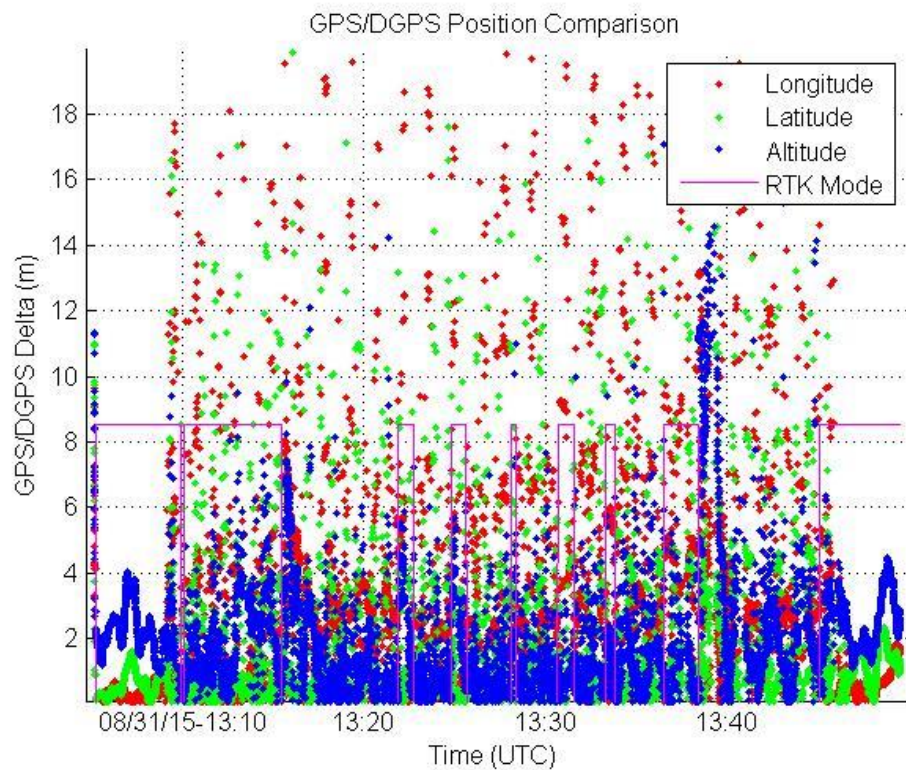


Figure 24: Carbon Cub GPS/DGPS Delta

The Hex Flyer flight data using an LK900 1W transmitter [Figure 25] show a small fraction of the flight data having Fixed-RTK position data. These data were collected using a 900 MHz telemetry Link and a 5.8 GHz Video Link. This system performance was unexpected since the aircraft attitude was well within system limits [Figure 26]. The rover satellite signals have very abrupt changes [Figure 27], which is very different from the Carbon Cub Piksi satellite flight data. It can be seen that the Piksi satellite signal interruptions are related to the noisy GPS/DGPS Delta plot sections [Figure 28]. Through additional ground testing it was learned that the telemetry link was causing DGPS satellite signal interference.

The signal interference in the rover DGPS satellite data can be seen by the abrupt dropping and returning of satellite signals. Based on the fact it is abrupt and not gradual during level steady hovering indicates the source of the problem is based on EMI. The only major emission difference between the Hex Flyer and the Carbon Cub would be: The additional 900MHz LK900

radio between the Hex Flyer A2 flight controller and the ground station laptop; As well as the 5.8GHz radio between the Hex Flyer AVL58 Videolink module and the ground station “First Person View” monitor/display. The Hex Flyer was flown with the radio emitters powered and unpowered with the results seen in the following figures.

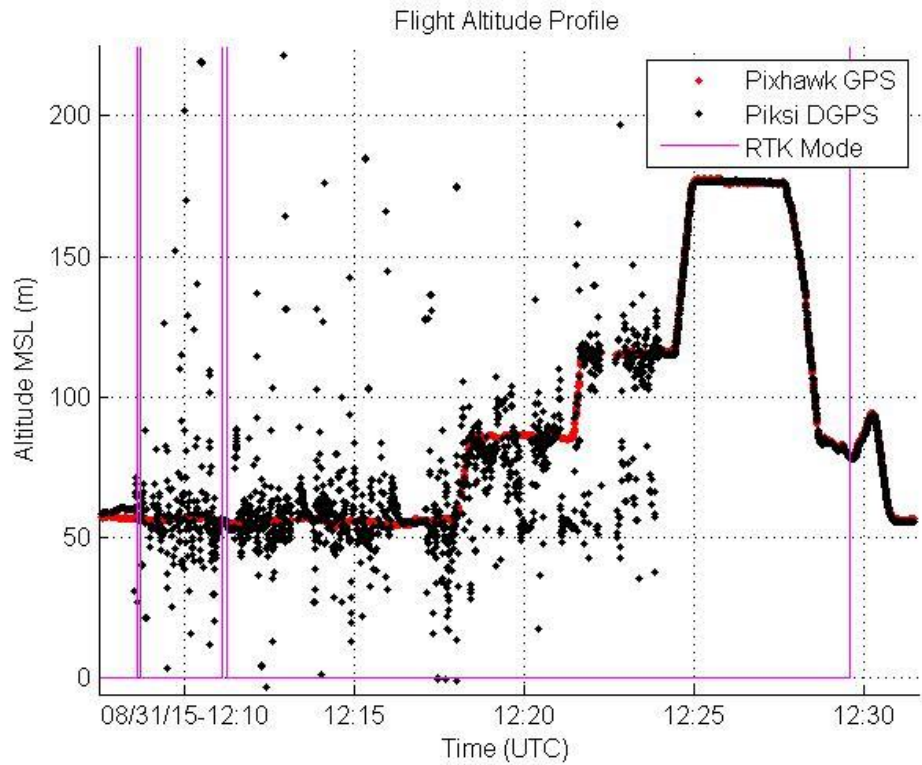


Figure 25: Hex Flyer Altitude w/LK900 & AVL58 Powered

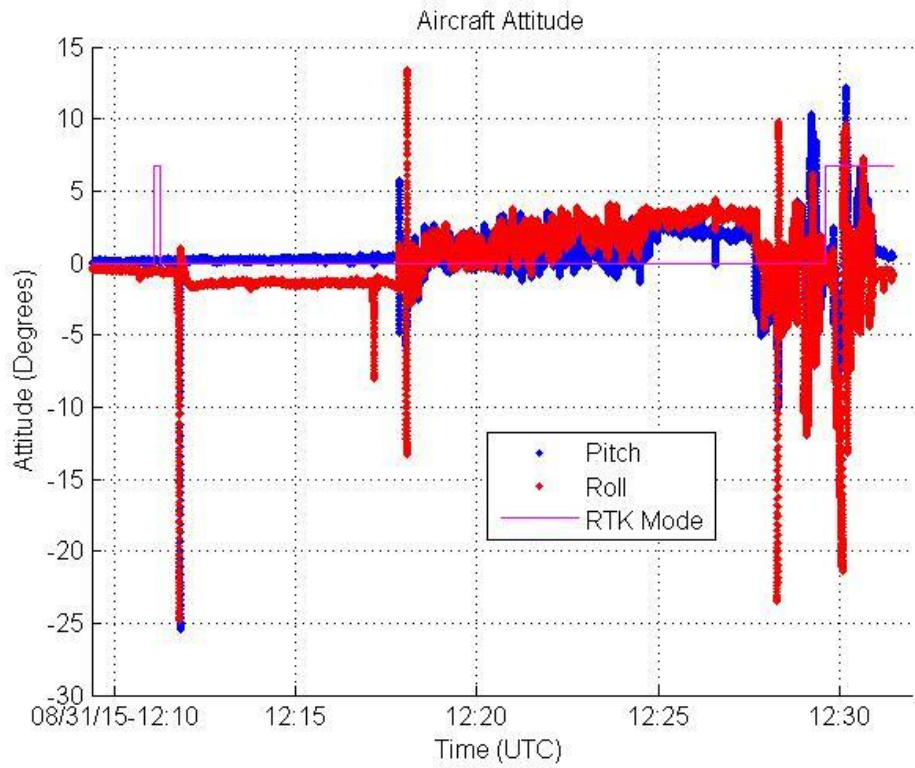


Figure 26: Hex Flyer Attitude w/LK900 & AVL58 Powered

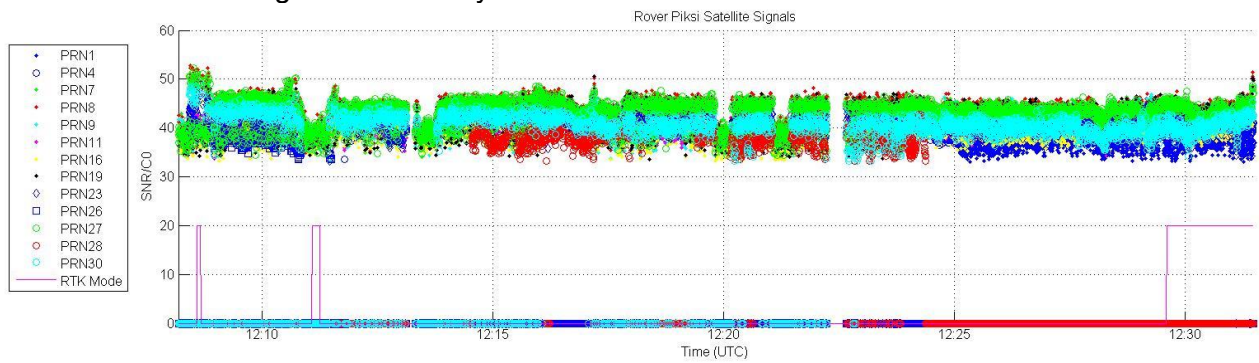


Figure 27: Hex Flyer DGPS Rover Satellite Signals w/LK900 & AVL58 Powered

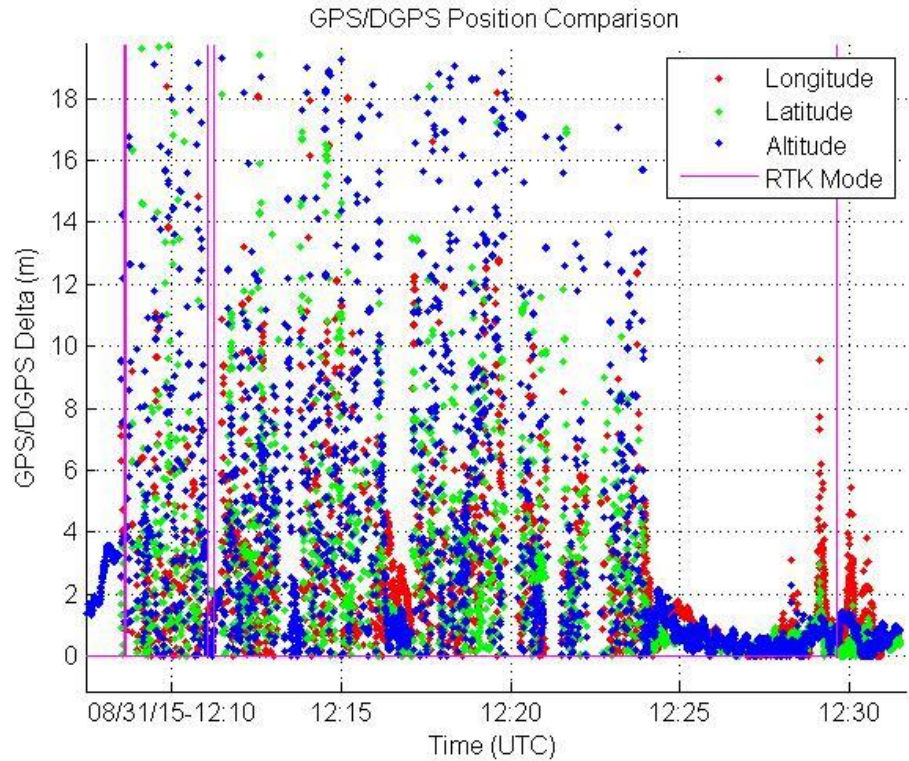


Figure 28: Hex Flyer GPS/DGPS Delta w/LK900 & AVL58 Powered

Hex Flyer flight data [Figure 29], with the LK900 and 5.8GHz video link disabled, showed all positional data as Fixed-RTK. With the flight well within the operational limits of the FDAS attitude limits [Figure 30] the relative error of the GPS position data can be seen. With nominal received satellite signals on the Piksi [Figure 31] the DGPS performance is expected to be reliable. The GPS/DGPS delta plot [Figure 32] looks good and shows us the relative error of the GPS system over the course of the flight. Under the assumption that the DGPS data is now the referenced truth the GPS system indicates an accuracy of $\pm 3\text{m}$, as expected.

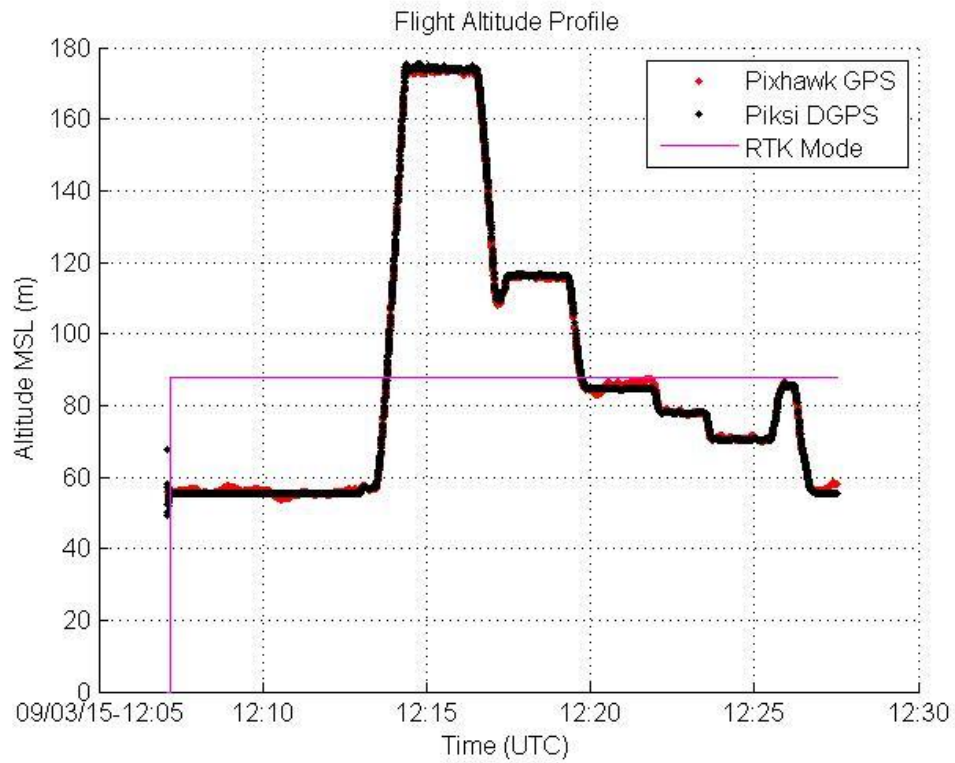


Figure 29: Hex Flyer Altitude w/LK900 & AVL58 Unpowered

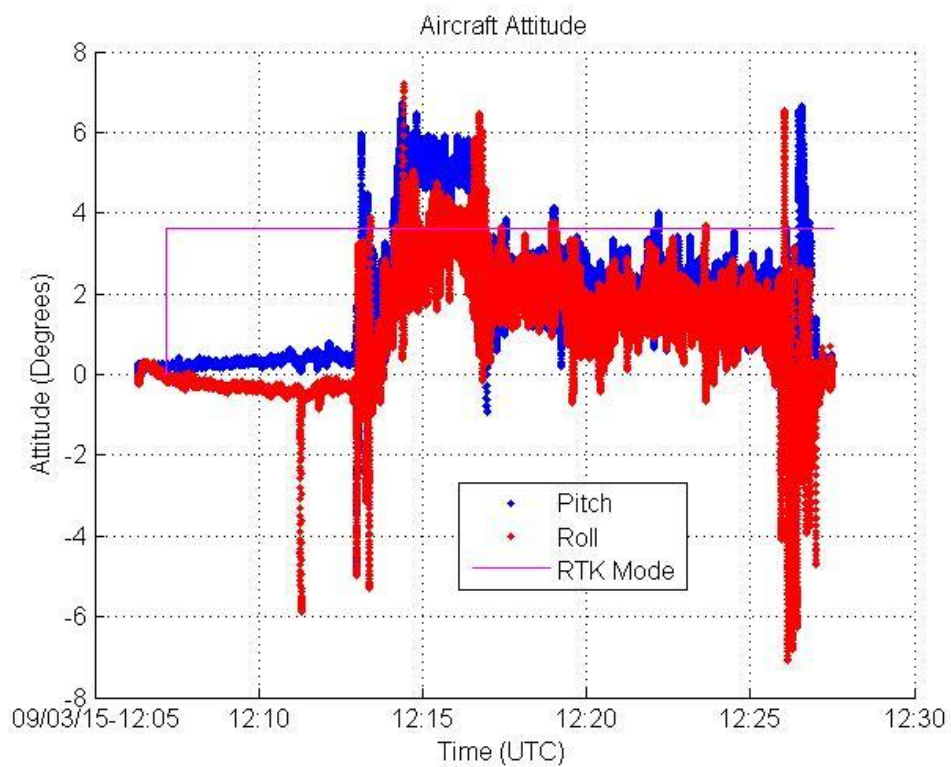


Figure 30: Hex Flyer Attitude w/LK900 & AVL58 Unpowered

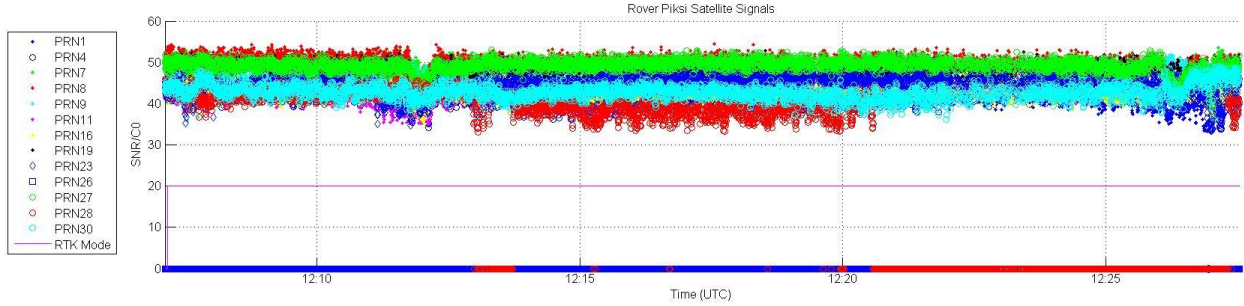


Figure 31: Hex Flyer DGPS Rover Satellite Signals w/LK900 & AVL58 Unpowered

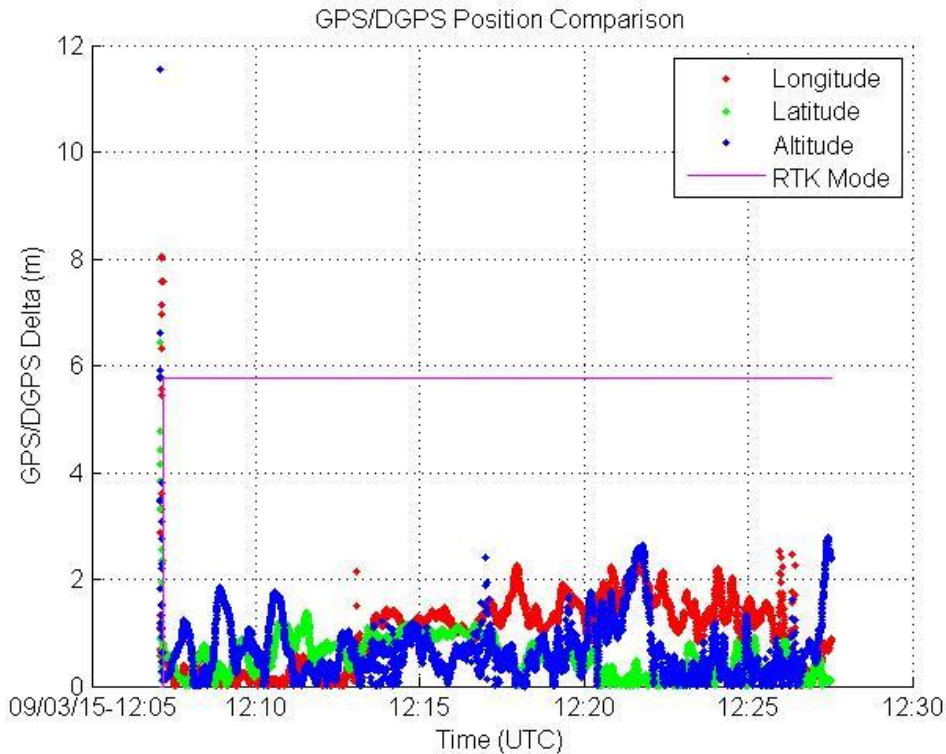


Figure 32: Hex Flyer GPS/DGPS Delta w/LK900 & AVL58 Unpowered

6. Conclusions

The FDAS successfully provides a low-cost heterogeneous sUAS independent flight data collection system on more than seven sUAS deployed on over thirty research flights. Reliable GPS latitude/longitude position accuracy up to 3 m (9.84 ft.) and altitude position accuracy up to 10 m (32.8 ft.) were observed as expected through ground and flight tests. DGPS relative north/east position accuracy up to 10 cm (3.9 in.) and altitude position accuracy up to 30 cm (12 in.) were observed during the ground and flight tests. Limitations for the DGPS positioning data include EMI, aircraft attitude and Piksi released firmware. EMI limitations were found when the DGPS data were lost when a 1W 900MHz LK900 transmitter was powered on during Hex Flyer integration build-up flights.

Attitude angles greater than forty-five degrees (pitch, roll) were observed to reduce the DGPS satellite signals. Throughout the year of testing and research, released Piksi firmware versions had a significant impact on the test results. Recommended solutions for these limitations include: EMI shielding of Piksi external antenna signal wire to mitigate interference and the addition of multiple external antennas to provide the needed satellite sky coverage during high angle attitudes flight operations. Future Piksi firmware updates will be limited until ground testing validates a performance increase.

6. Reference

1. Cabell, Randolph, Grosveld, Ferdinand, and McSwain, Robert, "Measured Noise from Small Unmanned Aerial Vehicles," Noise-Con 2016, Institute of Noise Control Engineering, Providence, Rhode Island, 13-15 June 2016.

REPORT DOCUMENTATION PAGE

Form Approved
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1. REPORT DATE (DD-MM-YYYY) 01- 08 - 2016			2. REPORT TYPE Technical Memorandum		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Development of Heterogeneous sUAS High-Accuracy Positional Flight Data Acquisition System					5a. CONTRACT NUMBER	
					5b. GRANT NUMBER	
					5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) McSwain, Robert G.; Grosveld, Ferdinand W.					5d. PROJECT NUMBER	
					5e. TASK NUMBER	
					5f. WORK UNIT NUMBER 533127.02.15.07.01	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) NASA Langley Research Center Hampton, VA 23681-2199					8. PERFORMING ORGANIZATION REPORT NUMBER L-20712	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001					10. SPONSOR/MONITOR'S ACRONYM(S) NASA	
					11. SPONSOR/MONITOR'S REPORT NUMBER(S) NASA-TM-2016-219335	
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category 06 Availability: NASA STI Program (757) 864-9658						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT Recently, a heterogeneous FDAS, consisting of a diverse range of instruments was developed to support acoustic flight research programs at NASA Langley Research Center. In addition to a conventional GPS to measure latitude, longitude and altitude, the FDAS also utilizes a small, light-weight, low-cost DGPS system to obtain centimeter accuracy to measure the distance traveled by sound from a sUAS vehicle to a microphone on the ground. Acoustic flight testing using the FDAS installed on several different sUAS platforms has been conducted in support of the NASA CAS DELIVER and ERA ITD projects (Reference 1). The first FDAS prototype was assembled and implemented in the acoustic/flight measurement system in December 2014 to support DELIVER acoustic flight tests. Evaluation of the system performance and results from the data analyses were used to further test, develop and enhance the FDAS over a six-month period to support acoustic flight research for the ERA						
15. SUBJECT TERMS Acquisition system; Design environment; Flight data; Integrated technology; Unmanned aerial system						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 29	19a. NAME OF RESPONSIBLE PERSON STI Help Desk (email: help@sti.nasa.gov)	
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (Include area code) (757) 864-9658	